

A New Approach to Parallel Interference Cancellation for CDMA¹

Dariusz Divsalar, Marvin Simon

Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Dr., Pasadena, CA, USA
Phone (818) 393-5138, fax (818) 354-6825
email: dariush@shannon.jpl.nasa.gov

and
Dan Raphaeli
Dept. of Electrical Engineering-Systems
Tel Aviv University, Tel Aviv, Israel

Abstract

This paper introduces an improved nonlinear parallel interference cancellation scheme that significantly reduces the degrading effect of user interference with implementation complexity linear in the number of users. The scheme operates on the fact that parallel processing simultaneously removes from each user a part of the interference produced by the remaining users accessing the channel the amount being proportional to their reliability. The parallel processing can be done in multiple stages. The proposed scheme uses tentative decision devices at the multiple stages to produce the most reliably estimated received data for generation and cancellation of user interference. Simulation results are given for a multitude of different situations, in particular, those cases for which the analysis is too complex.

1.0 Introduction

Multiuser communications systems that employ Code division multiple access (CDMA) exhibit a user capacity limit in the sense that there exists a maximum number of users that can simultaneously communicate over the channel for a specified level of performance per user. This limitation is brought about by the ultimate domination of the other user interference over the additive thermal noise. Over the years researchers have sought ways to extend the user capacity of CDMA systems either by employing optimum [maximum-likelihood (ML)] detection or interference cancellation (IC) methods [1-14]. With regard to the former, the work of Verdu [1,2] is perhaps the most cited in the literature and the one upon which much of the other work is based. In Verdu's work, the receiver structure is derived based on minimizing the squared Euclidean distance between the received signal and the sum of the M asynchronous user signals, i.e., the total transmitted signal. As such, the presence of all M users simultaneously sharing the channel is accounted for in arriving at the ML receiver. The primary difference between the structure that evolves from such an approach and

the conventional structure is that *joint sequence* decisions are made on the set of M matched filter outputs as opposed to individual bit-by-bit decisions on each matched filter output alone.

While indeed such optimum multiuser algorithms offer significantly improved performance by alleviating the disadvantages associated with the conventional scheme, they unfortunately suffer from the fact that their complexity grows exponentially with the number of users and the length of the sequence. This follows directly from the fact that the optimum ML decision algorithm can be implemented as a dynamic program with time complexity per binary decision that is $O(2^M)$ [15]. While in many practical applications such performance complexity prohibits implementation of the Verdu algorithm, its performance is still very much of interest since it serves as a benchmark against which to compare other schemes with less implementation complexity such as those that employ interference cancellation to be discussed shortly. Another disadvantage of the Verdu algorithm as well as most other multiuser detectors is the necessity of knowing the relative amplitudes of the various user signals present at the input to the receiver. One possibility around this disadvantage is to perform multiuser amplitude estimation [16]. An alternative scheme is to employ *power control* at the transmitter which is a common technique used in cellular radio systems to solve the near-far problem. In this case, all received users are assumed to have the same power.

The most obvious solution to the multiuser interference problem would be to design the user codes to have more stringent crosscorrelation properties since indeed if the signals were truly orthogonal this interference would not exist. Unfortunately, it is not theoretically possible that any set of codes will exhibit zero crosscorrelation in the asynchronous case. Moreover, the near-far problem mentioned above still exists even for well-chosen almost-orthogonal codes. Thus, the multiuser interference problem must be dealt with and tackled from another viewpoint.

One approach is the so-called *decorrelating receiver* [4]. In this method, the different users are made to become uncorrelated by a suitable linear transformation. This lin-

¹The research described in this paper was carried out at the JPL Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration, and was equally funded through the Director's Research and Discretionary Fund and Qualcomm, Inc.

ear transformation is computed by measuring all crosscorrelations between pairs of user codes and then inverting the resulting (typically huge) matrix of crosscorrelations. Since in practical systems each user is assigned a very long PN code, each bit has essentially a random code assigned to it. Thus, in this case, the above procedure would have to be repeated for each bit in succession! Also, since the code crosscorrelations are indeed random variables, it is also possible that the inverse of the crosscorrelation matrix might not exist.

Another popular approach is to employ interference cancellation, i.e., to attempt removal of the multiuser interference from each user's received signal before making data decisions. In principle, the IC schemes considered in the literature fall into two categories, namely, *serial (successive)* and *parallel* cancellation. With regard to the former, Viterbi [6] (see also Dent [7] and Patel and Holtzman [19]) suggested coordinated processing of the received signal with a successive cancellation scheme in which the interference caused by the remaining users is removed from each user in succession. One disadvantage of this scheme is the fact that a specific geometric power distribution must be assigned to the users in order that each see the same signal power to background plus interference noise ratio. This comes about because of the fact that with successive cancellation the first user to be processed sees all the interference from the remaining $M-1$ users whereas each user downstream sees less and less interference as the cancellation progresses. Another disadvantage of this scheme has to do with the required delay necessary to fully accomplish the IC for all users in the system. Since the IC proceeds serially, a delay on the order of M bit times is required to complete the IC for all users. Nevertheless, Viterbi showed that the successive IC scheme could approach channel capacity for the aggregate Gaussian noise channel. As such, the scheme does not become multiuser interference limited.

Parallel processing of multiuser interference *simultaneously* removes from *each* user the interference produced by the remaining users accessing the channel. In this way, each user in the system receives equal treatment insofar as the attempt is made to cancel his or her multiple user interference. As compared with the serial processing scheme, since the IC is performed in parallel for all users, the delay required to complete the operation is at best a few bit times. The early papers that dealt with parallel IC recognized the desire to arrive at a structure that could be motivated by the ML approach. In particular, a multistage iterative approach was suggested by Varanasi and Aazhang [8,9] which at a given stage estimated a given user's bit under the assumption that the exact knowledge of the other users' bits in the same transmission interval needed to compute the multiuser interference could be replaced by *estimates* of these bits from the previous stage. It was indeed this basic idea which led

to the multistage iterative schemes subsequently proposed by Yoon, Kohno, and Imai [11-13] and Kawabe et al [14]. What was common to all of these schemes was the fact that at each stage of the iteration, an attempt was made for each user to *completely* cancel the interference caused by all the other users.² As we shall see in this paper, this is not necessarily the best philosophy. Rather, when the interference estimate is poor (as in the early stages of interference cancellation), it is preferable not to cancel the entire amount of estimated multiuser interference.³ As the IC operation progresses, the estimates of the multiuser interference improve and thus in the later stages of the iterative scheme, it becomes desirable to increase the weight of the interference being removed. The motivation behind this approach can also be derived from ML considerations as was done for the total IC approach previously considered.

With the above discussion in mind, this paper presents a new parallel interference cancellation scheme that significantly reduces the degrading effect of multiuser interference but with a complexity linear in the number of users and with improved performance over the previously considered parallel and serial processing techniques. When compared with classical CDMA without IC, the improvement in performance is dramatic. Although our scheme is suitable to the case of a nonuniform power distribution as well as a uniform power distribution among the users, in this paper we shall primarily focus on the latter. In addition, although our scheme is applicable to asynchronous transmission, we shall assume here that all users have synchronous data streams. This case results in worst case performance, i.e., if the data transition instants of the various users are not aligned, then on the average they have less of an interfering effect on one another.

2.0 Multiuser Communication System Model

We consider a CDMA communication system in which M users are communicating simultaneously at the same rate over a common AWGN channel each with a BPSK data modulation and their own pseudonoise (PN) code. As such the received signal is the sum of M direct sequence BPSK signals each with power S_i , bit time T_b , and PN chip time T_c , and additive white Gaussian noise with single-sided power spectral density (PSD) N_0 W/Hz. At baseband, this signal can be written in the complex form⁴

$$r(t) = \sum_{i=1}^M s_i(t) + n(t) = \sum_{i=1}^M \sqrt{S_i} m_i(t) P N_i(t) e^{j\omega_c t} + n(t) \quad (1)$$

²We shall refer to such a technique as brute force or total interference cancellation.

³We shall refer to such a technique as weighted interference cancellation.

⁴For convenience, we shall use complex notation to represent the various signals in the receiver.

where for the i th user $PN_i(t)$ is the PN code waveform, $u_i(t) = \sum_{k=-\infty}^{\infty} a_k p(t - kT_b)$ is the data modulation with k th bit a_k taking on equiprobable values ± 1 and unit power rectangular pulse shape $p(t)$ of duration T_b (assumed for simplicity), and ϕ_i is the carrier phase. For the equal user power case, one would have, $S_i = S$; $i = 1, 2, \dots, M$.

We shall assume for the purpose of analysis and simulation that the users have purely random PN codes⁵ assigned to them. It is to be emphasized, however, that the IC schemes to be discussed in what follows apply equally well to any appropriate set of PN codes chosen for the users provided that the codes are known to the receiver. In view of our assumption, over the bit interval $0 \leq t \leq T_b$, the i th user's PN waveform can be expressed in the form

$$PN_i(t) = \sum_{k=1}^{\eta} c_{ik} p(t - kT_c) \quad (2)$$

where $p(t)$ is again a unit power rectangular pulse shape now of duration T_c , $\eta = T_b/T_c$ is the number of PN code chips per data bit, i.e., the spreading ratio, and $\{c_{ik}\}$ is a random binary (± 1) sequence. The user codes are specified in terms of their normalized cross correlation matrix $\gamma = [\gamma_{ij}]$ where

$$\gamma_{ij} = \frac{1}{\eta} \sum_{k=1}^{\eta} c_{ik} c_{jk} = \frac{1}{T_b} \int_0^{T_b} PN_i(t) PN_j(t) dt; \quad i, j = 1, 2, \dots, M \quad (3)$$

with $\gamma_{ii} = 1$; $i = 1, 2, \dots, M$.

3.0 Derivation of the New Parallel Iterated Multiuser Detector

As previously stated, the optimal multiuser detector [11] is derived from a joint ML decision on the M user data bits in a given interval and thus has exponential complexity in the number of users. Instead, we choose to *individually* decide on each user's data bit in this same interval, the motivation being to reduce the complexity of the detector. Clearly, in deriving such an ML metric for *any* one user, one would theoretically need *exact* knowledge of the data bits *corresponding* to all the other $M - 1$ users. Since indeed this information is unknown, the above *theoretical* assumption is *practically* invalid. However, by replacing *exact* knowledge of the other $M - 1$ user *bits* by estimates of their values, we arrive at an *iterative* scheme wherein each stage of the iteration produces new and better estimates of the user bits based upon those obtained in the previous stage. By solving this ML problem with the above condition imposed, we arrive at the following decision rule for the i th user (assumed herein to be the user of interest) at the k th iteration stage)⁶

⁵For very long linear feedback shift registers, PN codes can be assumed to be purely random.

⁶Interestingly enough, the suggestion to form a weighted sum as in

$$\hat{a}_i(k) = p_k (Y_i - \hat{I}_i(k-1)) + (1-p_k) \hat{a}_i(k-1) \quad (4a)$$

where $Y_i = \text{Re}\{e^{-j\phi_i} y_i\}$ with

$$y_i = \frac{1}{\sqrt{N_0 T_b}} \int_0^{T_b} r(t) PN_i(t) dt \quad (4b)$$

i.e., a normalized projection of the received signal on user i 's code, $E_b = S T_b$ is the bit energy in user i 's signal, and $\hat{I}_i(k-1)$ denotes the estimated interference contributed by the other users to user i and is given by

$$\hat{I}_i(k-1) = \sum_{j \neq i} \sqrt{\frac{2E_b}{N_0}} \hat{a}_j(k-1) e^{j(\phi_j - \phi_i)} \gamma_{ij} \quad (5a)$$

$$\hat{a}_i(k) = \tanh(\alpha_i \hat{a}_i(k)) \quad (5b)$$

In (5b), $\{\hat{a}_i(k)\}_{i=1}^M$ are the reliabilities of the bits at the $(k-1)$ st iteration (initially we have $\{\hat{a}_i(0)\}_{i=1}^M = \{Y_i\}_{i=1}^M$) and $\{\hat{a}_i(k)\}_{i=1}^M$ are the corresponding *tentative* estimated data bits which are obtained by employing a hyperbolic tangent form of decision device. (Other forms of decision devices are discussed below.) These decisions are referred to as tentative decisions (for any stage previous to the last) since indeed the final decision on the users data bits are only made at the last iteration stage, i.e., after the interference has been removed to whatever extent is possible. Fig. 1 is a multistage receiver structure with k th stage as in Fig. 2 which together form the weighted IC scheme suggested by Eq. (4). The significance of the parameters p_k in (4a) and α_k in (5b) as they relate to this structure are discussed below.

The parameter p_k ($0 \leq p_k \leq 1$) in (4a) is a *weight factor* in the k th iteration that represents the amount of cancellation attempted at that stage and is a parameter to be optimized for each value of k .⁷ Intuitively, one would expect that the value of p_k (which depends on the particular stage through the subscript k) would monotonically increase as one progresses toward the final data decision, i.e., as one iterates more and more, the fidelity of the tentative decisions improves and thus one should attempt to cancel more and more interference. Indeed, the numerical results to be presented later on bear out this intuition.

With regard to the form of tentative decision device used at each iteration stage for each user, there are several options. The hyperbolic tangent (soft decision) device, as indicated in (5b) is optimum from minimum mean-squared error (MMSE) considerations based on jointly observing Y_i and $\hat{a}_i(k-1)$ as opposed to Y_i alone. The specific way in which this new and improved iterative technique comes about is described in great detail in [18].

⁷For the unequal power user case, p_k also depends on the i th user's power and should be replaced by $p_{k,i}$.

error (MSF) considerations (based on a Gaussian interference assumption). Indeed this result was formally shown in [18] by considering $\hat{a}_i(k)$ as a nonlinear estimate of a_i given Y_i , $\hat{a}_i(k-1)$, and $\hat{I}_i(k-1)$. The best performance using this device will be obtained by optimizing the weight (slope) factors α_k in (5b). Another soft tentative decision is a linear device which is obtained by approximating $\tanh x$ by x in (5b), valid for small x . The linear decision device has the advantage that it does not require power estimates nor carrier demodulation; hence, a differential detection scheme can be employed instead of the coherent detection scheme assumed here. Finally, a hard decision can be used which provides a tentative bit polarity for the next iteration and corresponds to approximating $\tanh x$ by $\text{sgn} x$ in (5b), valid for large x . The merits of all these possibilities and others are discussed in more detail in [18].

4.0 Performance Results

The analysis of the performance of a single stage interference cancellation is given in [18] and is quite tedious to obtain despite many simplifying but valid assumptions. Extending the analysis to only two stages is even more complicated; hence, it is expeditious to obtain the performance of a k -stage iterative IC scheme from computer simulations. Software programs have been written to model user transmitters and the base station receiver in the complex baseband domain. Random PN codes are generated for each user and used to spread his or her random data bits. The results of these spreading operations are multiplied by the complex form of the carrier phases, $e^{j\phi_i} \Big|_{i=1}^M$, following which complex Gaussian noise samples are added to the combined received signal with at least one sample per chip time. The carrier phases which are generated independently for each user are assumed to be constant over the integration time of the detector and uniformly distributed in the interval $(0, 2\pi)$.

It is common in analyses of CDMA systems [17] to define a degradation factor, D , as the ratio (in dB) of the E_b/N_0 required to achieve a given bit error rate in the presence of M users, to that which would be required to achieve the same level of performance if only a single user was communicating. The performance results to be illustrated are plots of this degradation factor versus the number of users M for fixed values of processing gain η and bit error probability $P_b(F)$.

The proposed IC schemes were simulated with optimized values of the weight factors, P_k , up to three stages. The performance results described above are illustrated in Fig. 3 for linear and in Fig. 4 for nonlinear (hard decision) tentative decision devices along with the corresponding simulation and analysis results for a single stage brute-force (total cancellation) scheme. Also illustrated are the results

for conventional CDMA with no interference cancellation. We observe that, for the parameters considered and uncoded BPSK users, a three stage nonlinear IC scheme allows as many as 80 users with a degradation of only 1 dB as compared to 9 users in a conventional CDMA system with the same degradation. This ideally represents an almost nine-fold increase in the user capacity of the system.

5.0 Multipath Considerations

In both the analysis and simulation results presented here, we assumed an AWGN channel. If multipath is present and assumed to be known, then the following modifications of the above scheme would take place. First, in the description of the received signal, one would replace the modulation pulse shape $p(t)$ with its channel output version,

namely, $p'(t) = \sum_{l=1}^L h_l p(t - \tau_l)$, where L is the number of

multipath rays, τ_l are the multipath delays, and h_l the multipath channel coefficients. Next, the correlator in the receiver would be replaced by a RAKE combiner, and finally the respreader (multiplication of the tentative decision by the PN code) would be replaced by a circuit imitating the effects of the multipath on the PN code. This circuit should compute

$$\hat{a}_i PN_i(t) = \sum_{l=1}^L h_l PN_i(t - \tau_l) \hat{a}_i \quad (6)$$

6.0 Conclusions

The inclusion of multistage parallel interference cancellation in a CDMA receiver can significantly improve its performance relative to that of a conventional CDMA receiver where no interference cancellation is attempted. A weighted interference cancellation philosophy, in which the amount of interference cancelled is related to the fidelity of the tentative decisions involved in forming the interference estimate, is in general superior to a brute force philosophy of entirely cancelling the interference at each stage. Using a hyperbolic tangent device for making the tentative decisions at the various stages of the cancellation process is superior to using either a hard limiter or linear device. The linear device on the other hand has the advantage that the receiver implementation does not require knowledge of the user powers nor does it need carrier synchronization at the various stages. The latter implies that the final data decisions can be performed with a differential (rather than a coherent) detector. The technique is equally applicable to uncoded as well as coded modulations the latter being discussed in [18].

References

- [1] S. Verdu, "Minimum probability of error for asynchronous Gaussian multiple-access channels," *IEEE Trans. on Inform. Theory*, vol. 33, no. 1, January 1986, pp. 85-96.
- [2] S. Verdu, "Optimum multiuser asymptotic efficiency,"

IEEE Trans. on Comm., vol. COM-34, 110.9, September 1986, pp. 890-897.

[3] K. S. Schneider, "Optimum detection of code division multiplexed signals," *IEEE Trans. on Aero. and Electr. Syst.*, vol. AES-15, no. 1, January 1979, pp. 181-183.

[4] R. L. Upas and S. Verdu, "Linear multiuser detectors for asynchronous code division multiple access channels," *IEEE Trans. on Inform. Theory*, vol. IT-35, no. 1, January 1989, pp. 123-136.

[5] R. L. Upas and S. Verdu, "Near-far resistance of multiuser detectors in asynchronous channels," *IEEE Trans. on Comm.*, vol. COM-38, no. 4, April 1990, pp. 496-505.

[6] A. J. Viterbi, "Very low rate convolutional codes for maximum theoretical performance of spread-spectrum multiple-access channels," *IEEE Trans. on Sel. Areas in Comm.*, vol. 8, no. 4, May 1990, pp. 641-649. Also presented in part at the 1989 IEEE Comm. Theory Workshop.

[7] P. W. Dent, "CDMA subtractive demodulation," U. S. Patent 5,218,619, June 8, 1993.

[8] M. K. Varanasi and B. Aazhang, "Multistage detection in asynchronous code-division multiple-access communications," *IEEE Trans. on Comm.*, vol. 38, no. 4, April 1990, pp. 509-519.

[9] M. K. Varanasi and B. Aazhang, "Near optimum detection in synchronous code-division multiple-access systems," *IEEE Trans. on Comm.*, vol. 39, no. 5, May 1991, pp. 725-736.

[10] M. K. Varanasi and S. Vasudevan, "Multiuser detectors for synchronous CDMA communication over non-selective Rician fading channels," *IEEE Trans. on Comm.*, vol. 42, no. 2/3/4, February/March/April 1994, pp. 711-722.

[11] Y. C. Yoon, R. Kohno, and H. Imai, "Cascaded co-channel interference cancelling and diversity combining for spread-spectrum multi-access over multipath fading channels," Symposium on Inform. Theory and its Applications

(SITA '92), Minakami, Japan, September 8-11, 1992.

[12] Y. C. Yoon, R. Kohno, and H. Imai, "A spread-spectrum multi-access system with a cascade of co-channel interference cancellers for multipath fading channels," International Symposium on Spectrum Techniques and Applications (ISSSTA '92), Yokohama, Japan, November 29-December 2, 1992.

[13] Y. C. Yoon, R. Kohno, and H. Imai, "A spread-spectrum multi-access system with cochannel interference cancellation," *IEEE Jour. on Sel. Areas in Comm.*, vol. 11, no. 7, September 1993, pp. 1067-1075.

[14] M. Kawabe, T. Kate, A. Kawahashi, T. Sato and A. Fukasawa, "Advanced CDMA scheme based on interference cancellation," *Proc. of the 43rd Annual IEEE Veh. Tech. Conf.*, May 18-20, 1992, pp. 448-451.

[15] S. Verdu and H. V. Poor, "Abstract dynamic programming models under commutativity conditions," *SIAM Jour. of Control and Optimization*, vol. 25, July 1987, pp. 990-1006.

[16] H. V. Poor, "On parameter estimation in DS/SSMA formats," in *Advances in Communications and Signal Processing*, A. Porter and S. C. Kak, Eds., Springer-Verlag, New York, 1989, pp. 59-70.

[17] C. L. Weber, G. K. Huth, and B. H. Batson, "Performance considerations of code division multiple-access systems," *IEEE Trans. on Veh. Tech.*, vol. VT-30, no. 1, February 1981, pp. 3-10.

[18] D. Divsalar and M. K. Simon, "Improved CDMA Performance Using Parallel Interference Cancellation," JPL Publication 95-21, October 1995.

[19] P. Patel and J. Holtzman, "Analysis of a simple successive interference cancellation scheme in a DS/SSMA system," *IEEE Jour. on Sel. Areas in Comm.*, vol. 12, no. 5, June 1994, pp. 796-807.

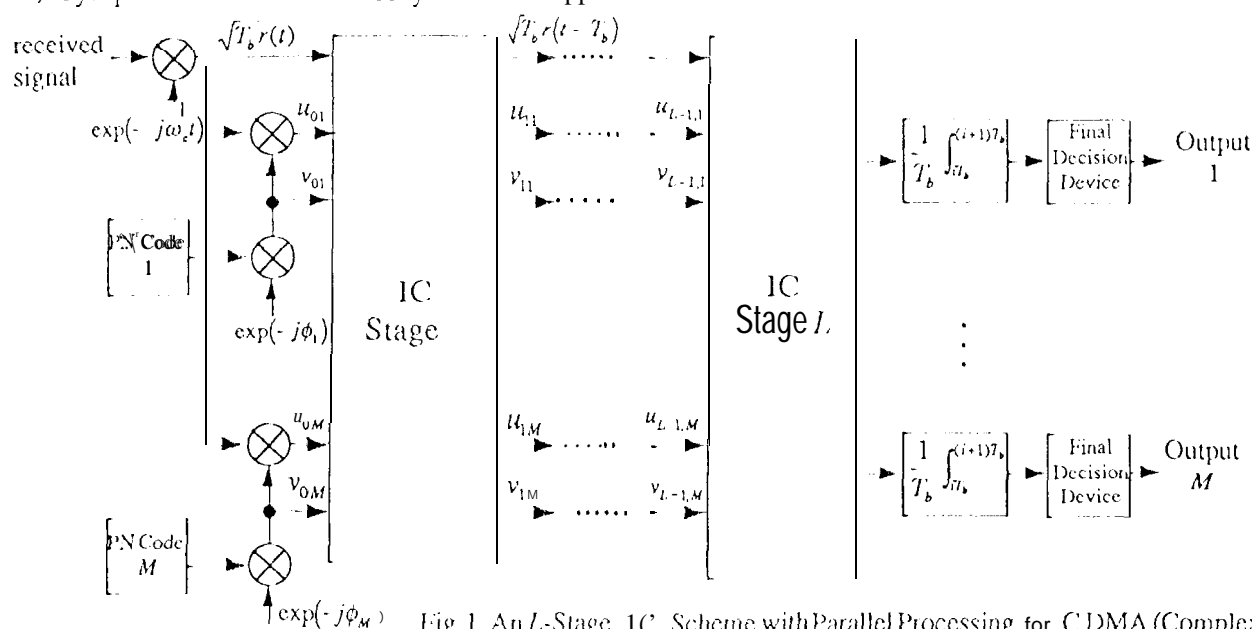


Fig. 1. An L-Stage IC Scheme with Parallel Processing for CDMA (Complex Baseband Model)

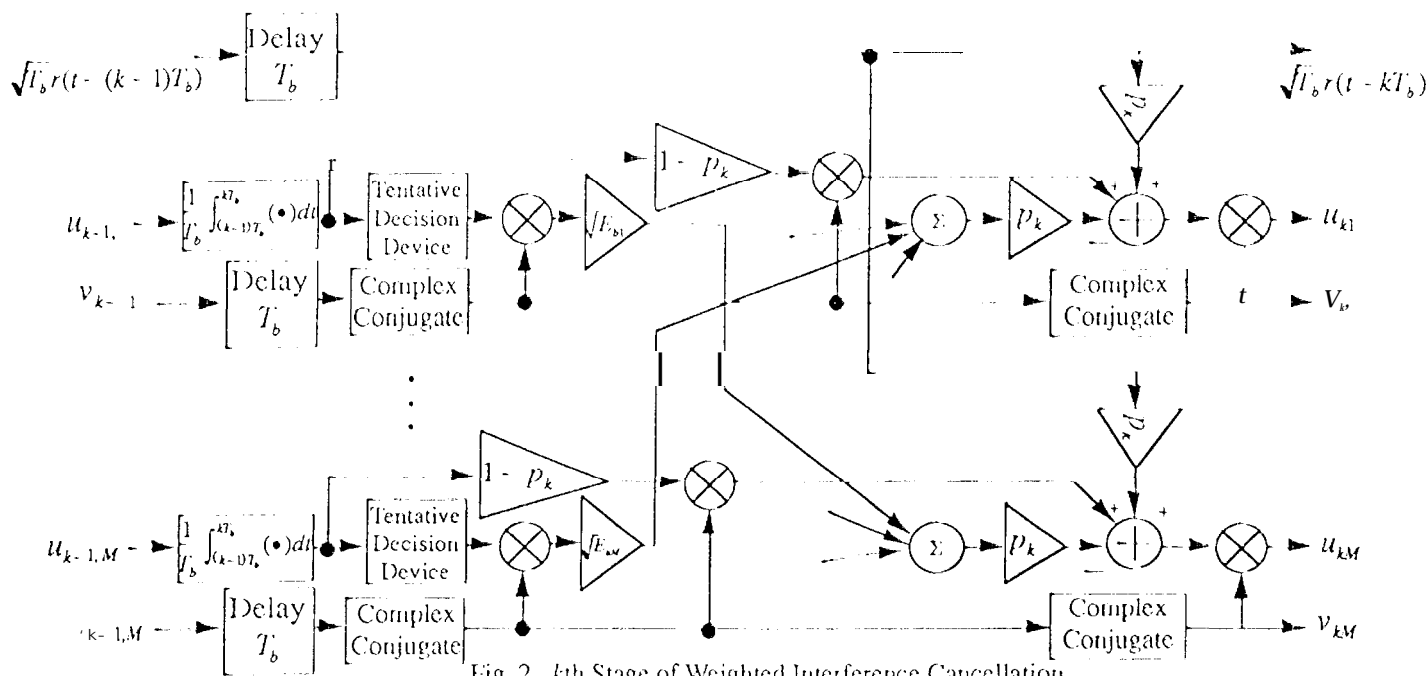


Fig. 2. kth Stage of Weighted Interference Cancellation

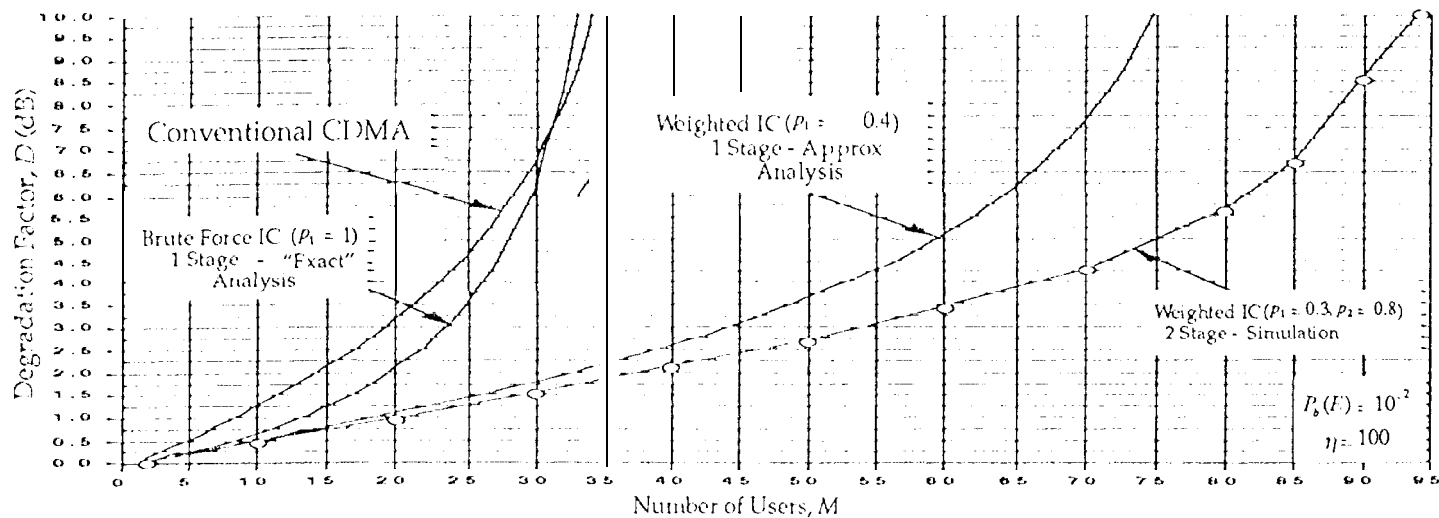


Fig. 3. Comparison of Degradation Factors for 1 and 2 Stage Linear IC - Equal Power Users

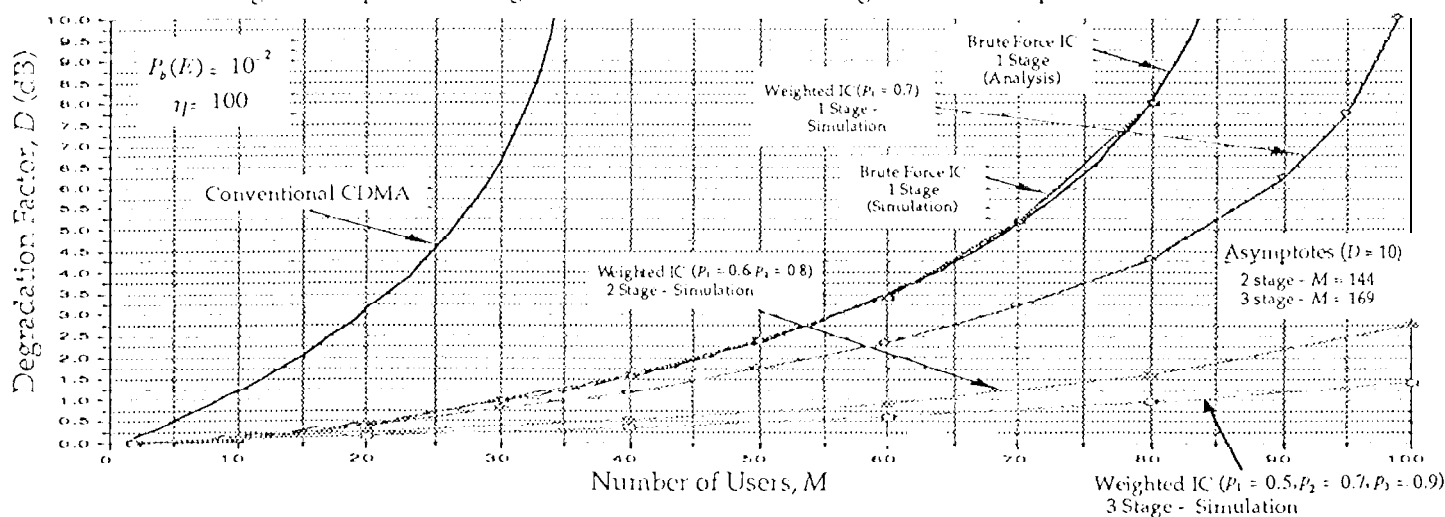


Fig. 4. Comparison of the Degradation Factors of 1, 2, & 3 Stage Nonlinear IC - Equal Power Users